Predicted and Measured Field Strengths in the Boulder, Colorado, Area from Two Proposed Terrestrial Digital Television Tower Sites

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A study was performed to determine the increase in ambient electromagnetic field strengths that would result from a proposal to locate a cluster of terrestrial digital television (DTV) transmission towers in proximity to the Department of Commerce (DOC) Laboratories in Boulder, Colorado. The primary objective of this study was to assess the impact on a broad range of Federal Government research and metrology programs that depend upon the relatively quiet radio-frequency electromagnetic environment. Radio-wave propagation measurements were performed for two terrestrial DTV frequencies (533 MHz and 772 MHz), and used to verify predicted DTV electric field strengths obtained from the DOC Irregular Terrain Model (ITM). The measured data were also used to determine the variation in received signal strength over small distance intervals. Radio-wave propagation measurements were performed at both frequencies using two possible mountaintop transmitter locations, Eldorado Mountain and Squaw Mountain. The first (Eldorado Mountain) affords substantial line-of-sight coverage over the Boulder area, and the second (Squaw Mountain) affords only indirect (diffractive) coverage over the same area. The two propagation conditions from each site, direct and indirect, respectively, are compared to the ITM predictions. The relative variations in measured and predicted signal strengths are compared as a function of frequency and of propagation conditions. Measured and predicted data were found to be in close agreement. This provides confidence that the theoretical predictions of received signal strengths at given locations in the Boulder area are accurate. It was found that in some locations, the ambient field strengths for 1 MW of transmitter power from a single station will exceed 1 V/m.

Key words: digital television (DTV), field strength measurements, Irregular Terrain Model (ITM), National Radio Quiet Zone (NRQZ), propagation modeling, spectrum survey

1. INTRODUCTION

The Federal Communications Commission (FCC) has mandated that all full-service (high-power) television broadcasters be transmitting a digital television (DTV) signal and be prepared to terminate their analog television (TV) broadcasts by 2006 [1]. In the United States, the analog television broadcast standard, or National Television System Committee (NTSC), allocates 6 MHz of bandwidth per channel [2, 3]. The high-power TV broadcasters have each been provided with a paired digital channel, usually in the "core" TV channels (2 through 51). If market penetration of digital television is sufficient, then the intent of the FCC directive is for analog TV broadcasts to cease and for some of the analog spectrum to be returned to the public for other communication services. In this report, the term DTV includes high-definition digital TV (HDTV). Current analog TV channels 52 through 69 will be reassigned to other uses, including the provision of additional spectrum for public-safety users (including a number of interoperability channels); some of this spectrum will also be auctioned for commercial wireless telecommunications network applications. Table 1 shows the present analog frequencies for the different TV channels along with the new DTV frequencies for some TV channels in the Denver, Colorado, Designated Market Area (DMA). Some of these TV channels have been authorized to transmit at effective radiated power (ERP) levels as high as one megawatt (1 MW), where ERP is defined as the product of the power supplied to the antenna and its gain relative to a half-wave dipole in a given direction [4]. The allocated power levels for these TV channels are also shown in table 1. Also shown in this table are the allocated power levels in units of equivalent isotropically radiated power (EIRP), defined as the product of the power supplied to the antenna and its gain relative to an isotropic antenna in a given direction [4]. Note, $\mathrm{EIRP} = 1.64\ \mathrm{ERP}$. EIRP is used throughout this report.

In Reference [1], the FCC indicates that in the future, adjustments to the allocated power levels may be granted under some situations, which would allow transmitter power levels higher than 1 MW ERP (1.64 MW EIRP). The Further Notice of Proposed Rulemaking (FNPRM) [5] indicates that maximum ERP of 5 MW (or 8.2 MW EIRP) is possible.

1.1 Electric Field Strength

A minimum DTV E-field strength of 41 dBμV/m (1.12×10^{-4} V/m) at a receiving antenna height of 9.14 m (30 ft) is assumed adequate to provide satisfactory reception, as recommended by the FCC [1]. Note that dBμV/m refers to decibels relative to 1 μV/m. The table of allotments was designed to essentially replicate a broadcaster's current analog Grade B coverage area with digital signal strengths greater than or equal to the minimum DTV electric field strength, while attempting to minimize analog-into-digital, digital-into-analog, and digital-into-digital co- and adjacent-channel interference with signals of other broadcasters. Transmitter power consumption is a significant operational cost, and it is therefore critical for broadcasters to have confidence that field strength prediction models are accurate, so that excessively high power levels are not transmitted. (High transmitter power can also increase deleterious interference, both into-digital and into-analog, for distant stations.) It is also critical for broadcasters to understand the amount by which received DTV signal strengths may vary spatially within predicted contours, so that power levels throughout the coverage area will be high enough to compensate for localities at which the actual field strength drops below the noise-limited field strength.

Reception may be possible with a 9.14 m outdoor antenna (this height assumes mounting 3 m above the rooftop of a two story residence) or indoor antenna; however, significant problems with reception with indoor antennas have been reported [6]. In this report, the Advanced Television Systems Committee (ATSC) Task Force has suggested that in order to overcome the indoor DTV reception problem, field strengths at the 9.14 m (30 ft) reference height may need to be increased substantially to 97 dBμV/m. This is an increase of 56 dB over the FCC 41 dBμV/m, which is equivalent to an increase by a factor of approximately 631 in field strength. This 56 dB increase can be obtained by either substantially reducing the coverage area of DTV reception or by increasing the allocated transmitter power levels by an unrealistic 56 dB.

In the Colorado Front Range (the Denver metropolitan area), several sites have been proposed as possible locations for the new DTV transmitting antenna towers. Two of these proposed sites are addressed in this report. They are on Eldorado Mountain, which is located just south of Boulder, Colorado, and on Squaw Mountain, which is located just south of Idaho Springs, Colorado. Note, the Eldorado Mountain and Squaw Mountain sites were chosen in this study because these two possible sites bound the propagation environment that would occur at both the Table Mountain NRQZ and the DOC Laboratories. The Eldorado Mountain site affords substantial line-of-sight coverage over the Boulder area, and the Squaw Mountain site affords only indirect (diffractive) coverage over the same area. The other possible tower sites fall between these two types of propagation conditions. The Department of Commerce (DOC) conducted tests and analyses to address whether DTV transmissions from these two proposed sites will produce E-field strengths that exceed the regulatory FCC limits for the Table Mountain National Radio Quiet Zone (NRQZ) north of Boulder, Colorado [8]. In addition, these tests were used to ascertain whether DTV transmissions from these proposed sites will have an adverse impact on measurement efforts that are performed on a regular basis at the DOC Laboratories located at 325 Broadway in Boulder, Colorado (hereafter referred to as the DOC Laboratories).

The DOC Laboratories in Boulder comprise three Federal research agencies: the National Institute of Standards and Technology (NIST), the National Telecommunications and Information Administration's (NTIA) Institute for Telecommunication Sciences (ITS), and the National Oceanic and Atmospheric Administration (NOAA). All three of these laboratories perform different types of measurement activities at both the Broadway location and at the Table Mountain NRQZ. The Table Mountain NRQZ is one of only two national radio quiet zones in the United States (the other being the National Radio Quiet Zone in West Virginia/Virginia [9]). The Table Mountain NRQZ provides scientists and engineers with a research environment where external radio signals (sometimes called "ambient radio noise") are kept to a minimum. The integrity of this NRQZ is mandated by both Federal regulation and state law, [8] and [10] respectively.

These regulations and laws require that signal strengths from various transmitters must not exceed specified E-field strengths within the Table Mountain NRQZ in frequency bands above 1.6 MHz (table 2). Other public and private institutions besides the DOC Laboratories use this NRQZ for research purposes. These include the United States Geological Survey (USGS), the National Center for Atmospheric Research (NCAR), the Deep Space Exploration Society (DSES), the Radio Amateur Satellite Corporation (AMSAT), and Coherent Technologies, to name a few.

In order to address the concerns of the DOC, propagation models were used to predict the E-field strengths at the two DOC locations (the Broadway Laboratories and the Table Mountain NRQZ). Various wave-propagation models have been developed that can be used for this task. They range from very simple free-space models to more complex irregular terrain models. Unfortunately, simple free-space models can be used only under certain conditions. A simple free-space model will give accurate results only when scatter-free line-of-sight conditions exist. However, the free-space model is a good starting point in considering broadcast field strengths and will be briefly summarized.

Consider the antenna in figure 1, which is connected to a transmitter. Assume that this system is isolated in free space (i.e., no scattering objects are in the vicinity of the antenna). With this assumption, it can be shown [11-14] that the power density ($\mathscr{P}$), and E-field can be related as follows

$$\mathscr{P} = \frac{\text{EIRP}}{4\pi R^2} \quad [\text{W/m}^2] \tag{1}$$

and

$$|E| = \sqrt{\eta\,\mathscr{P}} \quad [\text{V/m}], \tag{2}$$

where

$$\text{EIRP} = P_t G_t\,. \tag{3}$$

In these two expressions, EIRP is the equivalent isotropically radiated power, P_t is the input power at the transmitter antenna terminals (in units of watts), and G_t is the gain of the transmitter antenna, which is in general a function of directional angles θ (elevation) and ϕ (azimuth), relative to the antenna, in spherical coordinates. G_t is the gain relative to an isotropic antenna (often expressed in units of dBi, where dBi refers to antenna gain in decibels relative to an isotropic antenna). R is the distance (in units of meters) from the transmitter antenna to an observation point (the location of a receiver), and η is the free-space wave impedance given by the following

$$\eta = 120\pi \approx 377 \quad [\Omega]. \tag{4}$$

From the expressions given in equations (1) and (2), it is observed that the power density $\mathscr{P}$ decays as $\frac{1}{R^2}$ and the magnitude of the E-field decays as $\frac{1}{R}$. This is illustrated in figures 2 and 3, where the magnitude of the E-field and the power density are plotted as a function of R for an EIRP of 1 MW. Also shown in these figures are the IEEE radio frequency (RF) population exposure limits for a typical TV frequency [15], as well as some international limits [16]. Figure 2 also shows the 30 mV/m FCC Table Mountain NRQZ limit [8], which is given in table 2 for the DTV frequencies. Notice that for a distance of 23 km (the distance from Eldorado Mountain to the Table Mountain NRQZ) the free-space field value is about an order of magnitude higher than the FCC NRQZ limit. By inserting the NRQZ E-field limit into the expression given in equations (1) and (2), the minimal distance at which the FCC NRQZ requirement is met for a given transmitter power level and antenna gain can be obtained as follows:

$$R_{\min} = \left[\frac{\eta P_t G_t}{4\pi |E|^2} \right]^{1/2} \quad \text{[m]}. \tag{5}$$

For $|E| = 30\,\text{mV/m}$, $P_t = 1\,\text{MW}$, $G_t = 1\,\text{(EIRP=1 MW)}$, this reduces to

$$R_{\min} = 183 \;\; \text{[km]} \;\; \text{(or 114 mi)}. \tag{6}$$

Figure 1 represents an idealization of a realistic wave-propagation environment. A more realistic environment is depicted in figure 4. The figure shows a transmitting antenna on a hillside that propagates energy toward a receiving antenna near the ground. In this scenario the radio waves that propagate toward the receiving antenna are not simply the free-space environment shown in figure 1. As the receiving antenna moves along the ground and traverses the terrain profile, the E-field strength deviates from the free-space calculations due to effects of the terrain. In a line-of-sight (LOS) path, the transmitter can be physically seen from the receiver location, e.g., points A or C in figure 4. The E-field for a LOS path has contributions from a direct ray, reflected ray(s), and, to a lesser extent, from diffracted rays. The direct ray corresponds to the free-space result discussed above. The reflected rays are caused by multiple reflections due to objects in the environment (e.g., the ground, mountains, hillsides, trees, rocks, cars, buildings, people, etc.). The diffracted rays result from scattering from the edges of these objects. In a non-line-of-sight (non-LOS) path, the transmitter cannot be seen from the receiver location, e.g., point B in figure 4. The E-field for a non-LOS path is the result of contributions from only reflected rays and diffracted rays. In these cases, the direct, reflected, and scattered rays may add up constructively or destructively to cause the received signal strength to be larger or smaller than that predicted using the free-space model. In order to calculate the field strength in these more complex environments, sophisticated irregular terrain models must be used.

There are various irregular terrain models available for these calculations [17-19]. In the calculations presented in this report, the ITS Irregular Terrain Model (ITM) developed at the DOC Laboratories is used [17-20], which is based on the work of Longley and Rice [21]. This model was developed during the 1950's and 1960's and has been continuously improved throughout the years. For the predictions reported here, this model uses USGS digital terrain elevation data to determine the actual terrain profiles for the area of interest. Once the terrain features are determined, electromagnetic models are used to calculate the E-field strengths at any desired location given a transmitter's height, antenna gain, and power level. The ITM is widely used by the broadcast and communication industries.

In this report, we use the ITM to predict the E-field strengths at the DOC Laboratories and at the Table Mountain NRQZ for transmitters located at the proposed Eldorado Mountain and Squaw Mountain sites. However, to verify that the modeled results for the two proposed locations and tower heights are accurate, comparison to measured data is required. Since measurements of E-field strengths based on proposed transmitter tower heights (approximately 116 m (380 ft) at Eldorado Mountain and approximately 60.96 m (200 ft) at Squaw Mountain), and at the maximum proposed transmitting power levels (i.e., 1 MW ERP or 1.64 EIRP) are impractical, measurements were carried out at reduced transmitter antenna heights and power levels. The proposed transmitter tower heights for the two sites were obtained from either the landowners or public documents. The measurements were performed in the geographic area of interest to the DOC Laboratories at 533 MHz and 772 MHz, i.e., frequencies near the lower and upper ends of the UHF DTV spectrum allotment for several of the local broadcast stations. The propagation measurements were performed with fixed transmitters placed on the two mountaintops and a land-mobile receiver and data recording system. The two mountaintop locations used were the proposed Eldorado Mountain and Squaw Mountain sites. The mobile van-based receiver system was driven throughout the Boulder area, and E-field strengths were measured as a function of location across the area. Both line-of-sight and obstructed (shadowed) propagation paths were encountered during the measurements. For model validation, measured field strengths were compared to ITM calculated data as a function of location and frequency. The data also revealed the variation in received field strength as a function of location, for both line-of-sight and shadowed propagation. Once the model predictions were confirmed with the measurements, the ITM propagation model was used to calculate the E-field strengths for the proposed transmitter heights and power levels at the two proposed sites.

1.2 Organization of the Report

This report is organized as follows: Section 2 presents recently measured E-field strength at both the Table Mountain NRQZ and the DOC Laboratories, illustrating that the FCC E-field strength limits are currently maintained at the NRQZ and exhibiting the current field strengths at the DOC Laboratories. In Section 3, the measurement system is described and the measured data for the two different transmitter sites are shown. Also in Section 3, the measured data were scaled to the proposed transmitter power level to indicate the expected E-field strengths at both the DOC Laboratories and at the Table Mountain NRQZ north of Boulder. In Section 4, predicted E-field strengths obtained from the ITM are compared to the measured data. In Section 5, calculated E-field strengths are presented for the proposed antenna heights and power levels for the two different proposed transmitter sites. Section 6 discusses the FCC field strengths recommended for DTV reception. Also in this section, field strength plots for the FCC-recommended 9.14 m (30 ft) receiving antenna height are presented to illustrate predicted DTV reception in the Boulder–Denver area from the two proposed sites. In Section 7, antenna pattern effects are discussed. Section 8 discusses the effects of broadband transmission on sensitive measurement systems. Finally, we summarize the results and discuss the possible impact of the proposed sites on the scientific activities at both the DOC Laboratories and at the Table Mountain NRQZ facility.

In this report all measured data are scaled to a 1 MW EIRP and all the predicted E-field strengths are calculated for a 1 MW EIRP. Use of a 1 MW EIRP facilitates rescaling both the measured and calculated field strengths to any other desired EIRP level, as the need arises.

Table 1. Frequencies and power allocations for analog frequencies for the different TV channels along with the new DTV frequencies for some TV channels in the Denver, Colorado, Designated Market Area (DMA).

Current NTSC channel	Current frequency bands (MHz)	New DTV channel	New DTV frequency bands (MHz)	Allocated DTV ERP (MW)	Allocated DTV EIRP (MW)
2	54-60	34	590-596	1.0	1.64
4	66-72	35	596-602	1.0	1.64
6	82-88	18	494-500	1.0	1.64
7	174-180	17	488-494	1.0	1.64
9	186-192	16	482-488	1.0	1.64
12	204-210	38	614-620	1.0	1.64
14	470-476	15	476-482	0.099	0.164
20	506-512	19	500-506	0.248	0.407
31	572-578	32	578-584	0.233	0.383
41	632-638	40	626-632	0.0748	0.129
50	686-692	51	692-698	0.0817	0.134
59	740-746	43	644-650	0.01448	0.024

Table 2. Specified E-field strength limits for the Table Mountain NRQZ for the VHF and UHF frequency bands.

Frequency band (MHz)	E-field limit (μV/m)	E-field limit (dBμV/m)
1.6-470	10,000	80.0
470-890	30,000	89.5
>890	1,000	60.0